Charged Particles from Dark Matter: Galactic Propagation Effects

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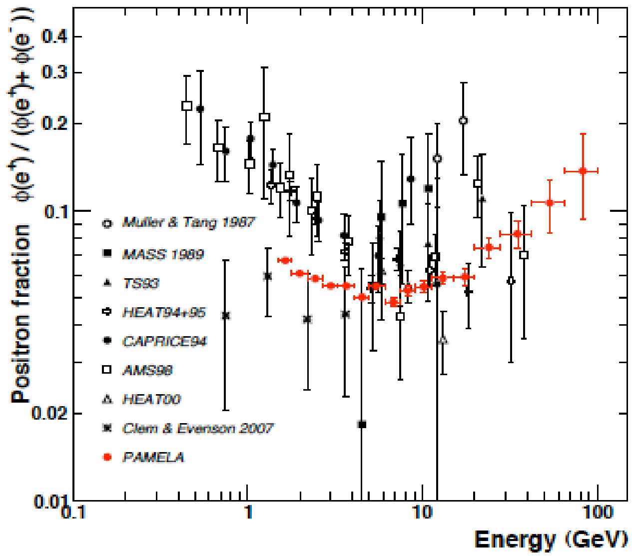
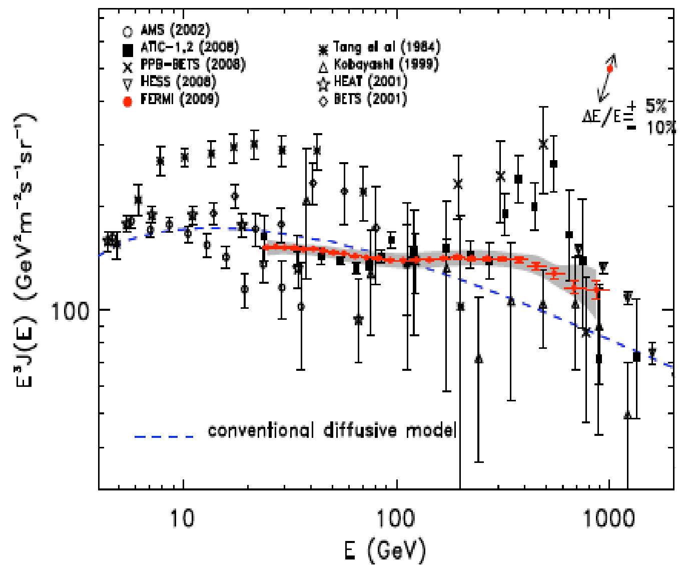
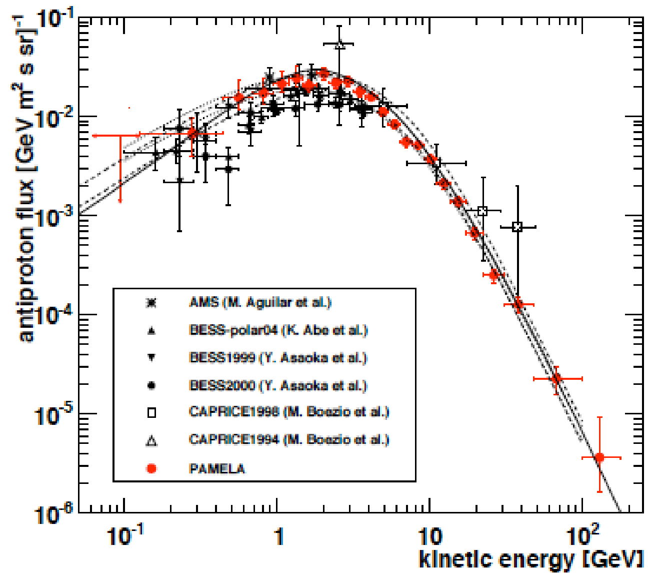
Based on arXiv: 1012.3772, 1002.4588 with Maxim Perelstein

Indirect Evidence of Dark Matter?







Data:
excess in e+ fraction and e^+e^- flux, no excess in antiprotons

Fit well to leptophilic dark matter annihilation with boosted cross sections in the galaxy

Connecting Theory to Observation

Spectrum observed experimentally

Annihilation cross section predicted by theory

$$\frac{d\phi}{dE} = \int_{E_{min}}^{m_\chi} dE' (\text{astrophysical correction}) \times \frac{d\sigma}{dE'}$$

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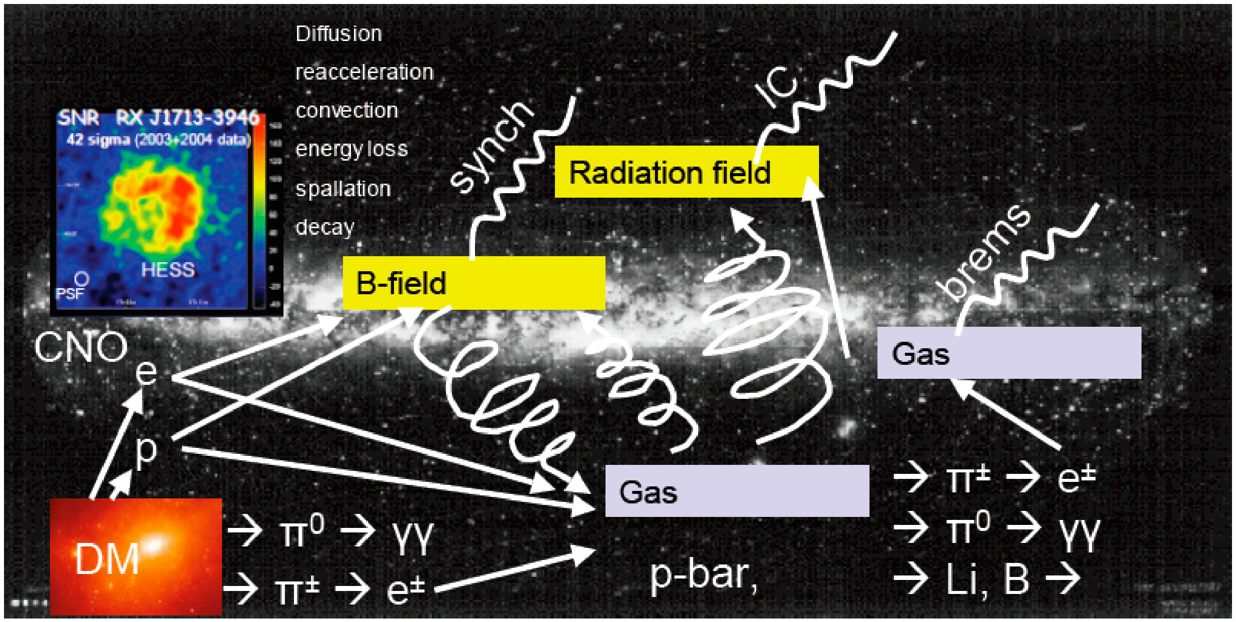
Spatial distribution of dark matter sources, propagation effects, interaction with interstellar matter….

(Nontrivial) Cosmic ray propagation in the galaxy

A mess! Electrons, positrons from dark matter annihilation interact with the galactic interstellar medium, losing energy and directional information.



From Jan Conrad's 08/07/09 talk at the SLAC Summer Institute

Galactic propagation significantly alters the spectrum

The diffusion equation (positrons)

$$-\nabla\left[K(\mathbf{x},E)\,\nabla\psi\right]-\frac{\partial}{\partial E}\left[b(E)\psi\right]=q(\mathbf{x},E)$$

Source term

Diffusion coefficient

position independent $K(E)=K_0\epsilon^\delta$

$\epsilon = E/E_0,\ E_0 = 1\ \mathrm{GeV}$

Energy loss rate

$$b(E)=\frac{E_0}{\tau_E}\,\epsilon^2$$

$\tau_E = 10^{16}\ \mathrm{sec}$

Positron density per unit volume per unit energy

Parameters defining a propagation model:

K, δ, L (size of region in which transport equation solved)

Model	δ	K_0 [kpc^2/Myr]	L [kpc]
MED	0.70	0.0112	4
M1	0.46	0.0765	15
M2	0.55	0.00595	1

The diffusion equation (antiprotons)

Convective wind term

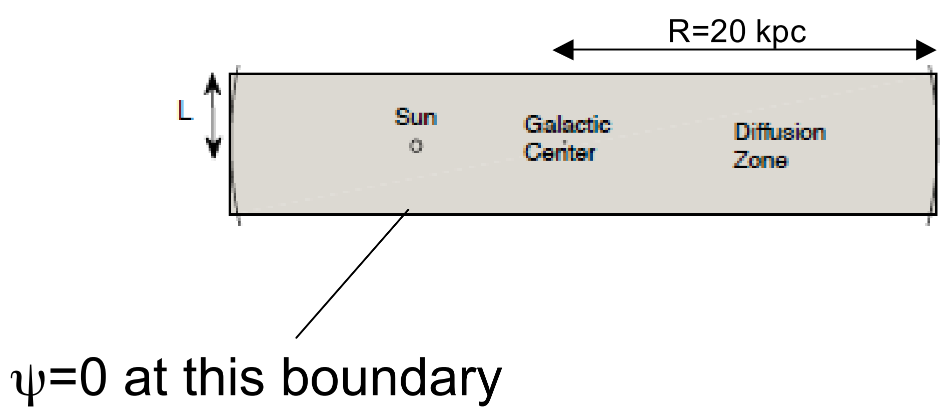
$$-\nabla\,[K(\mathbf{x},E)\,\nabla n_{\bar{p}}] + \frac{\partial}{\partial z}(V_C(z)n_{\bar{p}}(E,\mathbf{x})) + 2h\delta(z)\Gamma_{ann}n_{\bar{p}}(E,\mathbf{x}) = q_{\bar{p}}(\mathbf{x},E)$$

Antiproton interaction with interstellar medium, confined to galactic plane

Omitted: energy loss term (negligible for the more massive antiprotons)

Model	δ	K_0 (kpc^2/Myr)	L (kpc)	V_C (km/s)
MIN	0.85	0.0016	1	13.5
MED	0.70	0.0112	4	12
MAX	0.46	0.0765	15	5

Conventional approach: solve transport equation in a thin cylindrical disk (half-thickness L, radius R = 20kpc), the *diffusion zone,* where galactic magnetic fields confine positrons. Outside this region, positrons are assumed to propagate freely and escape.



Conventional Solution (positrons)

[T. Delahaye, R. Lineros, F. Donato, N. Fornengo and P. Salati, Phys. Rev. D 77, 063527 (2008)]

1. Write positron density as a Bessel-Fourier series

$$\psi(z,r,\epsilon) = \sum_i \sum_n P_{i,n}(\epsilon) J_0\left(\frac{\alpha_i r}{R}\right) \sin\left(\frac{n\pi(z+L)}{2L}\right)$$

2. Change variables as $t = \frac{\tau_E \epsilon^{\delta-1}}{1-\delta}, \quad \tilde{P}_{i,n} = \epsilon^2 P_{i,n}$

and take Bessel and Fourier transforms of the transport equation:

$$\frac{d\tilde{P}_{i,n}}{dt} + K_0\left(\left(\frac{\alpha_i}{R}\right)^2 + \left(\frac{n\pi}{2L}\right)^2\right)\tilde{P}_{i,n} = \epsilon^{2-\delta} Q_{i,n}$$

($Q_{i,n}$: Bessel-Fourier transform of source term q)

3. Solve to get: $\tilde{P}_{i,n}(t) = \int_0^t \tilde{Q}_{i,n}(t_S) \exp\left[-\omega_{i,n}(t-t_S)\right] dt_S$

where $\tilde{Q}_{i,n} = \epsilon^{2-\delta} Q_{i,n}$ and $\omega_{i,n} = K_0\left[\left(\frac{\alpha_i}{R}\right)^2 + \left(\frac{n\pi}{2L}\right)^2\right]$

Conventional Solution (antiprotons)

Expand antiproton density as a Bessel series

$$n_{\bar{p}}(\rho, z, E) = \sum_i N_i(z, E) J_0\left(\frac{\zeta_i \rho}{R}\right)$$

Assuming position independent K and V and solving in the cylindrical disk, the solution is

$$N_i(z) = e^{a(|z|-L)} \frac{y_i(L)}{B_i \sinh(S_i L/2)} \left[\cosh(S_i z/2) + A_i \sinh(S_i z/2)\right] - \frac{y_i(z)}{K S_i}$$

where

$$S_i = 2\left(a^2 + \frac{\zeta_i^2}{R^2}\right)^{1/2}, \quad A_i = \frac{V_C + 2h\Gamma_{ann}}{K S_i}; \quad B_i = K S_i \left[A_i + \coth(S_i L/2)\right]$$

$$y_i(z) = 2\int_0^z e^{a(z-z')} \sinh\left[S_i(z-z')/2\right] q_i(z') dz' .$$

$a = V_C/(2K)$

BUT these are extremely simplified propagation models, with many clearly unphysical approximations:

- The diffusion coefficient is position independent, but the diffusion behavior should be weaker away from the galactic center

- There is a sharp cutoff at the diffusion zone boundary, where the diffusion coefficient essentially gets an infinite jump

- The dark matter halo extends significantly beyond this disk, but these models neglect everything outside the diffusion zone boundary. (eg. for L=1 kpc and dark matter with an isothermal profile, the diffusion zone contains only ~10% of the dark matter mass.)

Justification: Simple, semi-analytic, easy to implement solutions.

Can do better: A more realistic setup

For antiprotons, the absence of an energy loss term allows significant analytic progress

Diffusion: charged particles getting confined by galactic magnetic fields $\longrightarrow$ diffusion coefficient should follow spatial variations of the galactic magnetic field strength

$$B(\rho, z) \approx (11\mu\mathrm{G}) \times \exp\left(-\frac{\rho}{10\ \mathrm{kpc}} - \frac{|z|}{2\ \mathrm{kpc}}\right) \Longrightarrow K(E, z) = K_e(E)\exp(|z|/z_t)$$

Has been studied numerically, have best fit parameters
(Evoli, Gaggero,Grasso,Maccione, JCAP 0810, 018 (2008))

For antiprotons, if the convective wind term is assumed to have a similar exponential profile (or can be neglected), CAN solve the diffusion equation analytically!

New Solution

$$N_i(z) \;=\; e^{a(|z|-L)}\,\frac{y_i(L)}{B_i\sinh(S_iL/2)}\;[\cosh(S_iz/2)+A_i\sinh(S_iz/2)] - \frac{y_i(z)}{K_eS_i}$$

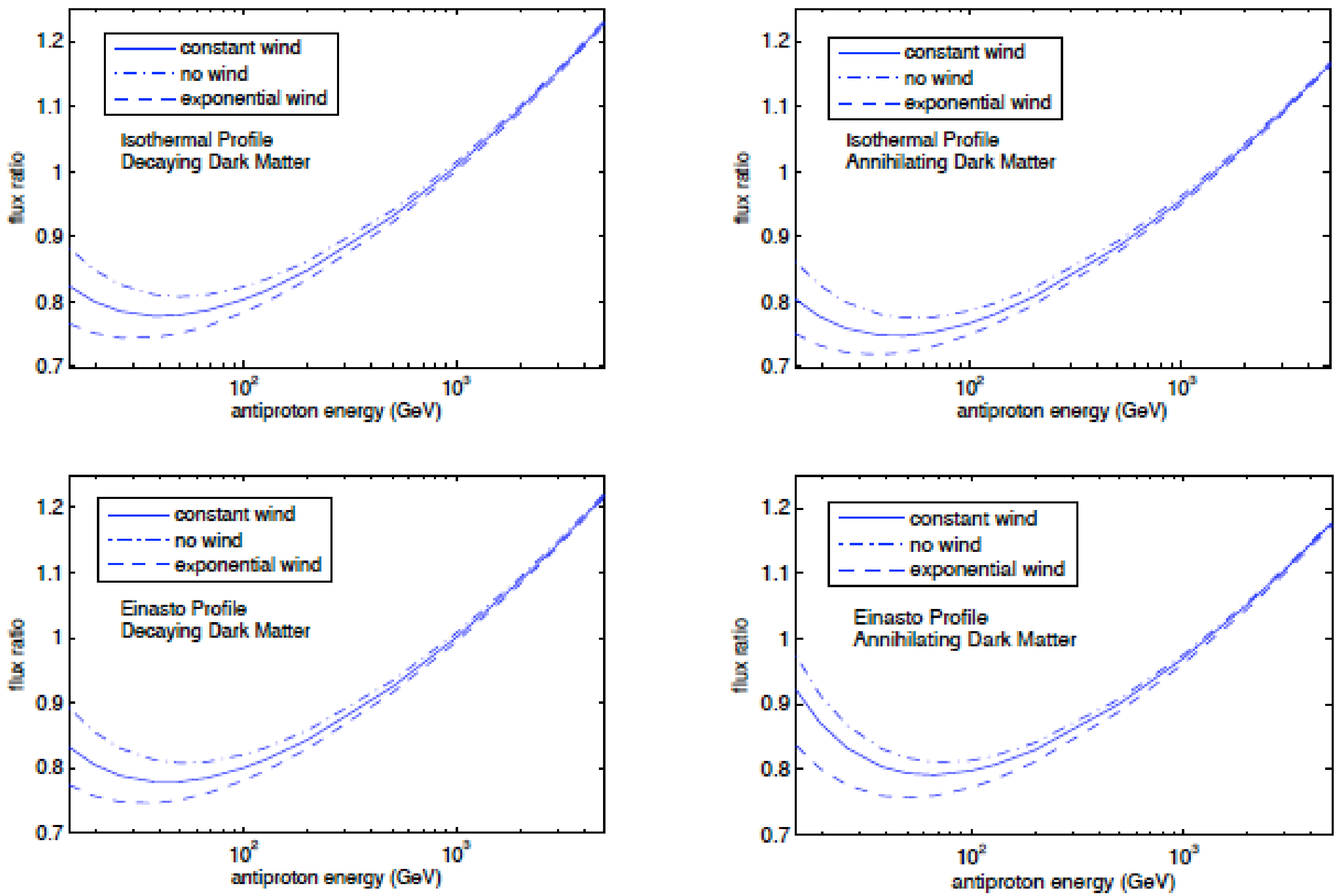
same form as the conventional solution, with slightly different definitions

$$\begin{aligned}
a \;&=\; \frac{V_e}{2K_e} - \frac{1}{2z_t}, \quad S_i \;=\; 2\left(a^2 + \frac{\zeta_i^2}{R^2} + \frac{V_e}{z_tK_e}\right)^{1/2}, \\
A_i \;&=\; \frac{V_e + 2h\Gamma_{ann}}{K_eS_i} + \frac{1}{z_tS_i}; \quad B_i \;=\; K_eS_i\,[A_i + \coth(S_iL/2)] \\
y_i(z) \;&=\; 2\int_0^z e^{a(z-z')}\,\sinh\left[S_i(z-z')/2\right]\,q_i(z')\,e^{-z'/z_t}\,dz'.
\end{aligned}$$

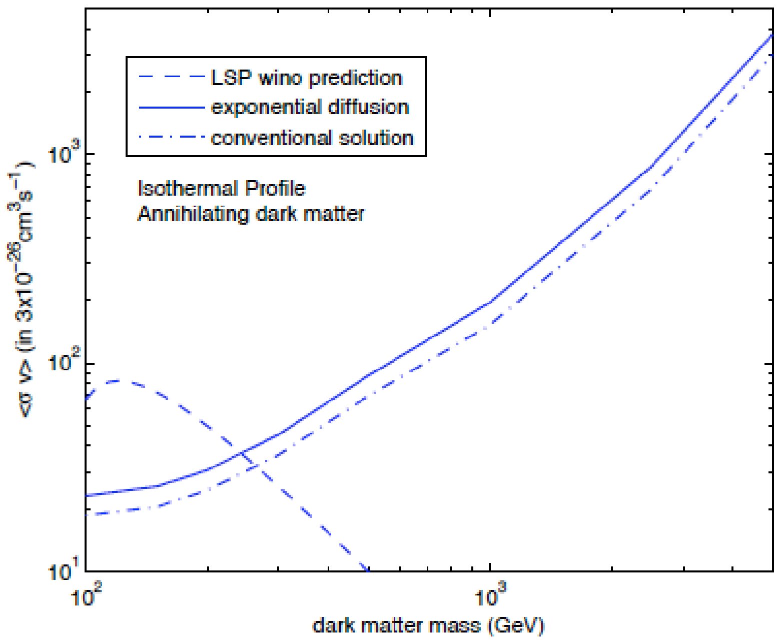
$$V_C(z) = V_e\exp(|z|/z_t)$$

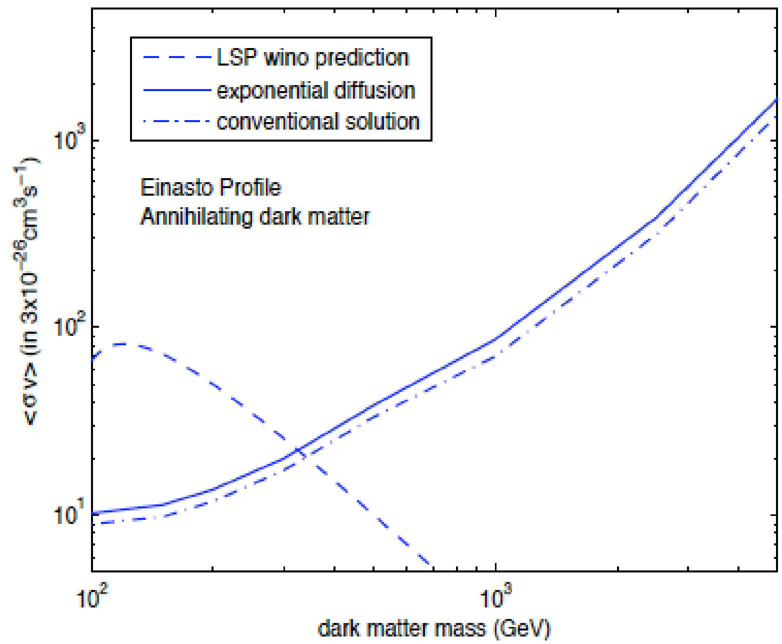
As simple to evaluate as the conventional solution!

Comparison with conventional solution



Antiproton bounds for WIMP dark matter

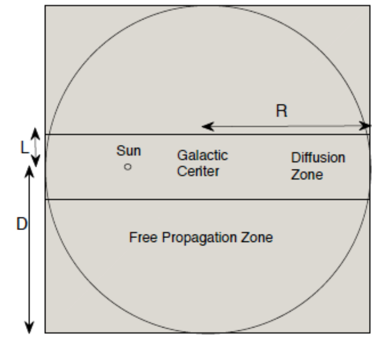




Assume stable dark matter pair annihilating into W^+W^-

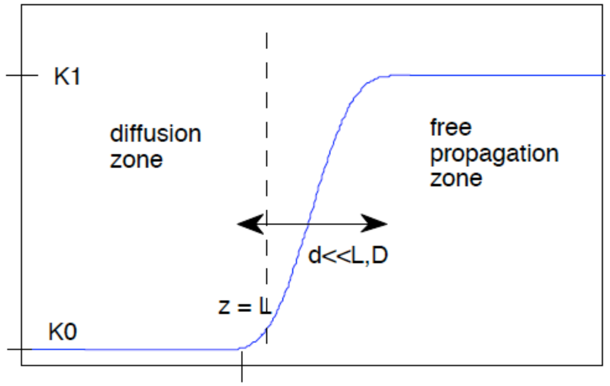
Bounds from conventional and new solutions agree to within ~20%

Correction for positrons



1. Set boundary condition at |z|=D, not |z|=L.

2. Make diffusion coefficient position dependent to incorporate different behavior in diffusion and free propagation zones



$$K(z,\epsilon) = \left(K_0 + \tilde{K}(z)\right)\epsilon^{\delta}$$

- Different modes mix, equations no longer decoupled.
- Diagonalize matrices numerically, compute solution.
- 10-15% enhancement in for MIN model, percent level correction for MED model.

Summary

• New, analytic, easy-to-use solution to antiproton flux from dark matter (valid at energies higher than several hundred GeV) in a more realistic propagation model, includes contributions from the full dark matter halo

• deviates from conventional solution by ~25% for realistic parameters

• Smaller correction for positrons, negligible for MED propagation

"When is science going to explain the dark matter I find in my belly button every morning?"

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Questions